Out-of-step Protection for Generators

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J. Berdy
Electric Utility Systems Engineering Department
General Electric Company
Schenectady, New York

During any stage of development of a power system, there will be some combination of operating conditions, faults or other disturbances which may cause the loss of synchronism between areas within a power system or between interconnected systems. If such a loss of synchronism does occur, it is imperative that the asynchronous areas be separated before generators are damaged or before a widespread outage can occur.

When a generator loses synchronism, the resulting high peak currents and off-frequency operation may cause winding stresses, pulsating torques and mechanical resonances that are potentially damaging to the turbine-generator. Therefore to minimize the possibility of damage, it is recommended the turbine-generator be tripped without delay, preferably during the first half slip cycle of a loss of synchronism condition.

Twenty years ago, generator, transformer and system impedance characteristics were such that the electrical center during a loss of synchronism generally occurred out in the transmission systems. Transmission line relaying or out-of-step relaying schemes could readily detect the loss of synchronism and in most instances the system(s) could be separated without the need for tripping generators.

With the advent of EHV systems, large conductor-cooled generators, and with the expansion of transmission systems, the impedances of generators, transformers and systems have changed appreciably. Generator and step-up transformer impedances have increased in magnitude while system impedances have decreased. As a result, on many systems today the electrical center during loss of synchronism conditions can and does appear in the generator or in the generator step-up transformer.

In general, the protection normally applied in the generator zone, such as differential relaying, time delay system backup etc., will not protect a generator during a loss of synchronism. The loss of excitation relay may provide some degree of protection but can not be relied on to detect generator loss of synchronism under all system conditions.[1] Therefore, if during a loss of synchronism the electrical center is located in the region from the high voltage terminals of the generator step-up transformer down into the generator, separate out-of-step relaying should be provided to protect the machine. This protection may also be required even if the electrical center is out in the system and the system relaying is slow or can not detect a loss of synchronism. Transmission line pilot wire relaying or phase comparison relaying will not detect a loss of synchronism.

It is the purpose of this paper to describe an out-of-step relaying scheme for generators and to discuss the various factors which must be considered in applying this protection on present-day generators and systems.

Loss of Synchronism Characteristics

Before out-of-step relaying can be applied to protect a generator, it is necessary to have some knowledge of the loss of synchronism characteristic as viewed from the generator terminals. This section reviews briefly the general loss of synchronism characteristic and then considers the characteristic for generators under various conditions.

General

The conventional relaying approach for detecting a loss of synchronism condition is by analyzing the variation in apparent impedance as viewed at the terminals of system elements. It has been shown[2,3,4] that during a loss of synchronism between two system areas or between a generator and a system, the apparent impedance as viewed at a line or generator terminals will vary as a function of the system voltages and the angular separation between the systems. This variation in impedance can be readily detected by impedance relaying and in most instances the systems or generator can be separated before the completion of one slip cycle.

Simplified graphical procedures have been developed[2] and used to determine the variation in apparent impedance during a loss of synchronism condition. These procedures derive an impedance locus which can be plotted along with the system characteristic on an R-X diagram. Typical impedance loci obtained with this procedure are illustrated in Fig. 1. It should be noted these three loci represent the variation in impedance as viewed at bus C (the origin) looking toward system B. This variation in impedance is illustrated for the straight line locus by the phasors Z_1, Z_2, Z_3, Z_4, Z_5.

The three impedance loci shown are plotted as a function of the ratio of the two equivalent system voltages E_A/E_B which is assumed to remain constant during the swing. Moreover, in this simplified approach, the following assumptions are made: initial transients (D-C or 60 Hz components) and effects of generator saliency are neglected; transient changes in impedance due to a fault or clearing of a fault (or due to any other disturbance) have subsided; effects of shunt loads and shunt capacitance are neglected; effect of regulators and governors are neglected; and the voltages E_A and E_B behind the equivalent impedances are balanced sinusoidal voltages of fundamental frequency.

When the voltage ratio $E_A/E_B = 1$, the impedance locus is a straight line LM which is perpendicular bisec-

tor of the total system impedance between A and B. On this diagram, the angle formed by the intersection of lines AL and BL is the angle of separation (δ) between the systems. If the system B(E_B) is taken as reference, and if it is assumed E_A advances in phase angle ahead of E_B, the impedance locus moves from point L toward M and the angle (δ) increases. When the angle (δ) reaches 120 degrees and goes beyond, the systems are considered unstable with this simplified approach.

When the locus intersects the total impedance line AB, the systems are 180 degrees out of phase. This point is both the electrical and impedance center of the system. As the locus moves to the left of the system impedance line the angular separation increases beyond 180 degrees and eventually the systems will reach a point where they will be in phase again. If the systems are not separated, system A will continue to move ahead of B again and the whole cycle repeats itself. When the locus reaches the point where the swing started, say at point L, one slip cycle has been completed.

The rate of slip between the two systems is a function of the accelerating torque and inertias of the systems. The slip can be obtained from transient stability studies where angular excursions of the systems are plotted versus time. From these plots, an average slip in degrees/sec can be determined. The slip between the systems will not be constant. However, the general practice is to assume a constant slip for the portion of the first slip cycle which is of interest; namely, the starting point of the swing locus and the point of 180 degrees separation between systems.

If system A slows down with respect to B (decreases in phase angle), the impedance locus will move in the opposite direction from M toward L.

When the voltage ratio E_A/E_B is greater or less than one (1), the impedance loci will be circles with their centers on extensions of the total impedance line AB. For the case of $E_A/E_B > 1$ the center of the circle will be in the (+X) region and the electrical center will be above impedance center of the system. For $E_A/E_B < 1$ the center of the circle will be in the (−X) region and the electrical center is below the impedance center. The diameters and the location of the centers of these circles are a function of the voltage ratio E_A/E_B and the total impedance. For a specific total impedance, as the voltage ratio increases above one (1), the circles decrease in diameter and centers move closer to the origin. Similarly for a specific total impedance, as the voltage ratio decreases below one (1), the circles also decrease in diameter and the centers move closer to the origin. This effect will be illustrated in the next section.

It should be noted that the electrical and impedance centers of the system are not fixed points. The location of these centers will also vary as the sytem impedances behind the line terminals vary. Therefore, when determining the impedance locus for a system, it is necessary to consider changes in system conditions (that is, variations in Z_A and Z_B of Fig. 1) and determine a locus for each condition.

Generator Loss of Synchronism Characteristics

In general, the loss of synchronism impedance loci as viewed at the generator terminals follows the swing characteristic where the voltage ratio E_A/E_B is less than one ($E_A/E_B < 1$). This is due to the fact that for most machine loadings, the equivalent internal machine voltage will be less than 1.0 per unit and less than the equivalent system voltage. This will generally be true for leading, unity and even for slightly lagging power factor loadings. Most generators are operated in this power factor range today.

Figures 2 to 5 illustrate the types of loss of synchronism impedance loci as viewed at the generator terminals that may be encountered for both tandem and cross compound generators that are connected to a system through some impedance. In all cases, the machine terminals are at the origin of the R-X diagram.

The impedance loci shown are given as a function of system impedance and were determined in a digital computer study using a comprehensive dynamic model of a steam turbine-generator. Representations of the excitation system and governor response were included and cases were considered with and without the voltage regulator in service.

In all cases, it was assumed that instability was caused by the prolonged clearing of a nearby three phase fault on the high voltage side of the generator step-up transformer. In these cases, the fault clearing times selected were between .18 to .2 secs.

Tandem Compound Generator. Figure 2 shows the loss of synchronism impedance loci as viewed from the terminals of a tandem compound generator for system impedances of .05, .2 and .4 per unit on machine base. The generator studied was a 475 MVA machine having the following characteristics:

Tandem Compound Conductor-Cooled Generator

475 MVA

22 kV 3600 RPM

Inertia Constant H = 3.0

$X_d = 1.96$ $X'_d = .285$

$X_q = 1.86$ $X''_d = X''_q = .225$

All impedances on machine MVA and voltage base.

The step-up transformer reactance was .15 per unit on machine base. In all three cases, the initial power output of the machine was .95 per unit at a lagging power factor and the voltage regulator was out of service.

In each instance, the loss of synchronism characteristic as viewed at the machine terminals is a circle whose center is below the R axis. The point P represents the initial load impedance, point S

represents the short circuit impedance (S = XT) when the fault is applied and point R represents the apparent impedance the instant the fault is cleared. The change from P to S and from S to R is instantaneous. After the fault is cleared the impedance locus moves in a counterclockwise direction as shown in Fig. 2

As can be seen in Fig. 2, with a .05 per unit system impedance, the impedance locus is a small circle and the electrical and impedance centers are below the origin inside the generator. For the higher system impedances (.2 and .4 per unit), the impedance locus increases in diameter and the electrical and impedance centers shift from within the machine out into the step-up transformer. This increase in circle diameter and shift in electrical center is due to the fact that as the system impedance is increased, a higher initial internal voltage (higher excitation) is required to produce 1.0 per unit voltage at the machine terminals and at the system bus than with the lower system impedance. As a consequence, the .4 system impedance case has the highest internal machine voltage, while the .05 system impedance case has the lowest internal machine voltage. In all three cases, the ratio of internal machine voltage to system voltage is less than one (1).

As noted in a previous section, the diameters and the location of the centers of these circles are a function of the ratio of internal machine voltage to system voltage. When this ratio is less then one (1), the impedance locus is a circle with its center in the (-X) region. Also as the voltage ratio decreases, the diameter of the circle decreases and the center moves closer to the origin. These points are illustrated by the three loci shown in Fig. 2.

Aside from the differences in internal voltages, these loci also reflect the decay in these voltages during the fault. With the omission of the voltage regulator, the internal machine voltages will decay during the fault and will remain at the resulting lower level after the fault is cleared. The field time constant is such (T'_{dO} = 5 sec) that the internal voltage will not change appreciably for a number of slip cycles. This decrease in internal voltage produces impedance loci having smaller diameters which may be more difficult to detect.

When the effects of a voltage regulator are included, the impedance locus circles are larger in diameter but will still be within the generator zone. Figure 3 illustrates the effect of a .5 response excitation system which will reach ceiling in 1 to 2 seconds. The impedance locus circles are shown for .05 and .2 per unit system impedances. With this slow response system, the initial swing, and the electrical center have not changed appreciably from that shown in Fig. 2.

With the voltage regulator in service, the decay in internal voltage is offset by the increase in excitation produced by the voltage regulator and therefore the internal voltage is essentially kept at the pre-fault level for several slip cycles. The diameters of the circles shown in Fig. 3 are proportional to the pre-fault voltage.

Cross Compound Generator. Figures 4 and 5 show the impedance loci for a cross compound generator as a function of system impedance. The generator studied had the following characteristics:

Cross Compound Conductor-Cooled Generator

909 MVA

High Pressure Unit	Low Pressure Unit
475 MVA	434 MVA
22 kV, 3600 RPM	22 kV, 1800 RPM
H = 1.565	H = 6.05
$X_d = 1.96\ X_q = 1.66$	$Xd = 1.76\ X_q = 1.65$
$X'_d = .285$	$X'_d = .26$
$X''_d = X''_q = .225$	$X'_d = X'_q = .165$
Impedances on 475 MVA base	Impedances on 434 MVA base

The step-up transformer reactance was .15 per unit on 909 MVA base, initial power output was .95 per unit at a lagging power factor, and the voltage regulator was out of service. All system impedances are in per unit on 909 MVA base. All cases show the impedance loci as viewed at the terminals of the high pressure unit (HP), the low pressure unit (LP) and a composite characteristic as viewed at the low voltage terminals of the step-up transformer. As before, the loss of synchronism was due to the prolonged clearing of a nearby three phase fault just outside the high voltage terminals of the step-up transformer.

Figure 4 illustrates the impedance loci for a system impedance of .05 per unit. In this case, the impedance loci, curves A and B, as viewed at the terminals of the LP and HP units are similar to those shown in Fig. 2 for a tandem compound generator. The HP unit with its lower inertia has completed one slip cycle while the high inertia LP unit has completed a small portion of a slip cycle. In this instance, the HP unit loss of synchronism characteristic could be used to detect the loss of synchronism of both units. The composite characteristic as viewed from the terminals of the step-up transformer curve C is small and irregular and would not be suitable to use for the detection of a loss of synchronism. The reason for this will become evident in the discussion of protective schemes in the next section.

Figure 5 illustrates typical impedance loci when the system impedance falls in the range of .2 or .4 per unit. In this case, the impedance loci, curves A and B, as viewed from the terminals of the LP and HP units are irregular and are above the R axis. Because of irregularity of these loci, they would not be suitable to use for the

detection of a loss of synchronism. On the other hand, the composite characteristic as viewed from the terminals of the step-up transformer curve C follows the same pattern as for a tandem compound generator and could be used to detect the loss of synchronism for both units.

While not shown, the effect of a voltage regulator is to increase the size of the loss of synchronism characteristics as illustrated in the tandem compound generator cases.

Generator Slip

Generator angular velocity or slip may be determined in terms of degreeslsec or in slip cycleslsec where 360 degrees is equal to one slip cycle.

For the tandem generator, the average slip during the first half slip cycle will generally be in the range of 250 to 400 degreeslsec (.694 to 1.11 slip cycleslsec) while for the cross compound units, the average initial slip will be 400-800 degreeslsec (1.11 to 2.22 slip cycleslsec). For both types of generators, the average slip during the remainder of the slip cycle will fall in the range of 1200-1600 degreeslsec (3.33-4.44 slip cycleslsec). It should be noted, these slips are approximate values. The actual slip varies continuously with time and will be a function of the machine inertias and the length of time it takes to clear the fault. In general, the longer the fault clearing time the higher the initial slip.

As a point of interest, generator overspeed during a loss of synchronism is equal to one (1) plus per unit slip, where per unit slip is equal to slip cycleslsec divided by 60, the reference frequency. Therefore if a generator has an angular velocity of 4 slip cycleslsec, the machine per unit speed S will be $S = 1 + \frac{4}{60} = 1.067$ per unit speed or the machine will be operating at 6.7% overspeed.

OUT-OF-STEP RELAYING SCHEME

The scheme recommended for generator loss of synchronism protection is the CEX-CEB blinder scheme. This scheme utilizes three impedance measuring units and logic circuitry to evaluate the progressive change in impedance as would occur during a loss of synchronism and to initiate tripping when the angle between generator and system voltages in 90 degrees or less. Switching at this angle (90 degrees or less) is generally recommended in order to minimize the duty on the circuit breaker(s). When properly applied, this scheme is capable of initiating tripping during the first half slip cycle of a loss of synchronism condition. Since a loss of synchronism is essentially a balanced three-phase phenomenon, the relay units used in this scheme are, and only need be, single phase devices.

CEX-CEB Electromechanical Blinder Scheme

This scheme utilizes two angle impedance elements, type CEX, and an offset mho unit, type CEB, as a supervisory relay. The characteristics of the relays as applied at the terminals of a generator are shown on an R-X diagram in Fig. 6 The two angle impedance elements or blinders designated as 21ST/A and 21ST/B, have straight line characteristics that can be adjusted to be approximately parallel to the system impedance line. The spacing between blinders can be adjusted to detect a loss of synchronism at various angles of separation between generator and system. In this case, the relays are set for a angle of separation (δ) equal to 120 degrees. The blinder A will pick up for impedances that appear to the right of the characteristic while blinder B will pick up for impedances to the left of the characteristic. These blinders in conjunction with logic circuitry analyze the variation in apparent impedance and determine whether or not a loss of synchronism has occurred.

The offset CEB unit, 21M, supervises tripping and is basically used to prevent incorrect operation for stable swings and to limit tripping to a safe angle. This unit would be set to detect all unstable swings appearing in the generator or in the step-up transformer. The need for this unit will be discussed in detail in the application section.

The operation of the scheme is simple and straightforward. Figure 6 shows the relay characteristics and an assumed impedance locus (F-K). Proper operation of the scheme depends upon the impedance locus entering the offset mho unit and crossing both blinder characteristics. By the time the impedance locus reaches area H the mho relay, the blinder elements and associated auxiliary relay logic have ascertained a loss of synchronism has occurred and the decision to trip has been made. Tripping is permitted when the impedance locus leaves the offset mho characteristic. At this point, the angle of separation between generator and system will be 90 degrees or less.

The logic for this scheme is shown in Fig. 7. This diagram shows the blinder contacts (21ST/A1, 21ST/A2, 21ST/B1, 21ST/B2) offset mho contacts (21M/a, 21M/b) and six auxiliary relays which provide the necessary logic. The blinders and their associated logic (X_1, X2, X_4, X_5) operate independently to determine a loss of synchronism but their trip output (X_3) is supervised by the mho 21M/a contact through 21M/X. This assures that tripping is only established for a swing which goes through the CEB zone. Final tripping is permitted by 21M/b only when the swing leaves the CEB characteristic. Figure 6 indicates the area of closure of the 21ST/A and 21ST/B blinder contacts Al, A2, B1, B2. For example, when an impedance is to the right of blinder B, 21ST/A2 and 21ST/B2 are closed. When the impedance is between the blinders, 21ST/A2 and 21ST/B1 are closed and when the impedance is to the left of blinder A, 21ST/A1 and 21ST/B1 are closed. It should be noted, that under normal steady state conditions load impedance will be somewhere along the + R axis and therefore 21ST/A2 and 21ST/B2 will be closed and XI will be picked up.

Considering Fig. 6 and the logic diagram of Fig. 7, the

step by step operation of the scheme for an impedance swing would be as follows:

STEP **1.** The impedance locus appears at F. 21ST/A2 and 21ST/B2 and two X_1 contacts are closed. 21ST/A1 and 21ST/B1 are open.

STEP 2. The impedance locus enters the offset mho characteristic. Auxiliary X picks up closing 21 MIX in the X3 trip relay circuit. 21 M/b opens in the trip circuit.

STEP 3. Impedance locus now enters the area G between blinder characteristics. 21ST/B2 opens and 21ST/B1 closes. While Xl is deenergized, it has time delay dropout and therefore the Xl contacts remained closed. The closure of 21ST/B1 causes X2 to pickup through contacts 21ST/A2 and Xl. X2 seals in the Xl contact and closes a contact in the X3 trip relay circuit.

STEP 4. Impedance locus moves to reion H to the left of blinder A. 21ST/A1 closes, 21ST/A2 opens and 21ST/B1 remains closed. Relay X2 is deenergized but its contacts remain closed because of time delay dropout. Closure of 21ST/A1 picks up auxiliary X4 which completes the X3 trip relay circuit. This circuit seals in and the X3 contacts close in the trip circuit.

STEP 5. The impedance locus enters region K. The CEB drops out closing 21 M/b, thus permitting tripping.

The above description assumes an impedance swing from right to left (F to K) which will always be the case for generator loss of synchronism. However, the scheme will provide correct operation for swings in either direction and therefore is applicable for out-of-step tripping out on the transmission system.

Scheme Capability

The CEX-CEB scheme was recently tested to determine the limits of scheme operation as a function of slip, relay current level and relay settings. This testing was performed on scale model generators at the Electric Power Systems Engineering Laboratory at the Massachusetts Institute of Technology. The generators used in this test were developed at MIT in cooperation with the American Electric Power Service Corp.[5,6] and are physical scale models of generators at the Big Sandy, Mitchell and Amos stations on the American Electric Power System. The model generators have a power rating of about one millionth of that of their counterpart and have per unit reactances, time constants and inertia constants which are almost identical to the actual machines. The excitation system, the voltage regulator and governor characteristics are also modeled to duplicate those of the actual machine. The voltage regulator was not used in the testing of the CEX-CEB in order to obtain the most pessimistic results.

The relays tested were a CEX17E with adjustable range 1.5-15 ohms and a CEB51 having a forward adjustable reach of 3-30 ohms and an offset adjustable reach of O-4 ohms. The scheme was applied at the terminals of the generator with the relays set as shown in Fig. 6. The forward reach of the CEB was set to look into the generator while the offset was set to encompass the transformer reactance and some system impedance.

With these settings, the system impedance was varied to produce an impedance locus which went below the R axis and a locus which went above R axis in the CEB offset region.

With the impedance locus below the R axis, the relay current was 11.3 amperes when the generator and system were 180 degrees out of phase. Under this condition the scheme tripped in the first half slip cycle for slips up to 2700 degreeslsec or 7.5 slip cycles. This slip is equivalent to a machine speed of 112.5%. The scheme was able to detect this high rate of slip even when the blinders were set at their minimum reach which was equivalent to an angular separation between generator and system of about 140 degrees.

With the impedance locus above the R axis, the relay current was 9.6 amperes. The reduction in current was due to the higher system impedance required to bring the swing above the R axis. Under these conditions and with the blinders set for 120 degree angular separation, the scheme tripped in the first half slip cycle for slips up to 2400 degreeslsec or 6.7 slip cycleslsec. This slight reduction in capability was attributed to the slightly slower operating time of the CEB in the offset region.

When the current in the relays was reduced from 11.3 and 9.6 amperes down to 5.7 and 4.8 amperes, with the generator and system 180 degrees out of phase, the scheme tripped in the first half slip cycle, for slips up to 1440 degreeslsec or 4 slip cycleslsec for impedance loci above and below the R axis. This slip is equivalent to a machine speed of 106.7%.

As noted in the preceding section, machine slips during the first half slip cycle will normally be in the range of 250 to 800 degreeslsec (or .69 to 2.22 slip cycles per sec) which is well within the capabilities of the scheme. The maximum expected slip of a steam turbine generator during a loss of synchronism condition would normally fall in the range of 1296 to 1728 degreeslsec which is equivalent to 6 or 8 percent overspeed.

The relay current during a loss of synchronism is a function of generator, transformer and system impedance; machine internal voltage and equivalent system voltage; and current transformer ratios. Under the most limiting conditions, the relay current will generally fail in the range of 7 to 12 amperes, which is also well within scheme capability. This subject will be discussed im more detail in the following section.

APPLICATION OF OUT-OF-STEP RELAYING

The application of out-of-step relaying schemes on a generator, or for that matter out on a system, is not a simple procedure. In general, the proper application of these schemes requires extensive stability studies to determine the following:

1. Loss of synchronism characteristics (impedance loci).

2. Maximum generator slip.

3. Characteristic of stable swings.

4. Expected current levels in the relays.

Each of these factors will be considered separately.

Loss of Synchronism Characteristics

The discussion in the section on Loss of Synchronism Characteristics has presented some typical loss of synchronism impedance loci for tandem and cross compound generators. However, it should be noted these characteristics are the result of generalized studies that do not consider all types of generator designs, voltage regulator characteristics, system parameters or the interaction effects of other generators. In general, the impedance loci as viewed at the generator terminals will not be smooth circles as indicated in Figs. 2 to 4 but may be distorted due to the interaction effects of other generators. For example, Fig. 8 shows the interaction effects on a generator's impedance locus in a stability study involving a large system. As noted, the traverse of the locus is irregular as it dips in and out of the generator zone.

Therefore, it is recommended that stability studies be performed to determine the location and characteristic of the loss of synchronism impedance loci for each generator on a specific system. These impedance loci should be determined with system configurations which give maximum and minimum systems impedances and with voltage regulators in and out of service. In general, with low system impedance and voltage regulator out of service, the impedance loci will be smaller in diameter and therefore more difficult to detect. This point will be illustrated in a subsequent section. High system impedance with voltage regulator in service causes the impedance loci to go through the step-up transformer and the location of these loci can influence the required relay settings.

Generator Slip

The slip for a particular generator can only be determined from transient stability studies. As was mentioned earlier, the average slip can readily be estimated from a plot of generator angular change versus time during an unstable swing. Only the maximum slip is of importance and need be determined to ascertain that this slip is within the capability of the relaying scheme. This maximum slip will be a function of generator inertia, accelerating torque and fault clearing times. Maximum accelerating torques will be produced by close in three phase faults on the high voltage system. Maximum possible backup times should be considered in clearing such faults. There has been a downward trend in generator inertias which has tended to increase machine slips. Typically two pole steam generator units have intertia constants H in the range of 2-3; four pole steam generators have an H = 3.5 to 4.5; hydro generators have an H approximately equal to 4; single shaft gas turbines have an H = 6 to 8; and double shaft gas turbines have an inertia constant (H) approximately equal to 2.

Stable Transient Swings

In the description of the CEX-CEB blinder scheme, it was noted that the CEB unit was used to prevent incorrect operation of the scheme for stable swings. Under certain conditions, it is possible for the impedance locus due to a stable transient swing to cut across the blinder characteristics and thus set up the necessary logic for tripping. The conditions that lead to these types of impedance swings are:

1. The generator is initially operating at unity or leading power factor.

2. Voltage regulator out of service.

3. Low system impedance.

4. The clearing of a three phase fault on a line just outside the high voltage terminals of the step-up transformer at the critical switching time. (That is, the maximum switching time for which the machine is just stable.)

To illustrate the extent of these swings, Fig. 9 shows the impedance loci for stable transient swings as viewed from the generator terminals as a function of machine loading and system impedance. This figure gives the impedance loci for three values of system impedance and for two machine loadings: full load - unity power factor; full load - .95 leading power factor. In all cases, the voltage regulator was out of service and a high voltage three phase fault was cleared at critical switching time. The point L represents the initial load impedance; point S represents the short circuit impedance (S = XT) when the fault is applied, and point R represents the apparent impedance the instant the fault is cleared. The change from L to S and from S to R is instantaneous.

Curves A and B show the impedance loci for the case of the machine operating at full load - unity power factor. For the .2 per unit system impedance, the impedance locus curve A swings to the right and away from the origin. The swing makes several oscillations before settling down to the initial load point. For the .05 per unit system impedance, the impedance locus swings down and actually makes a more extensive excursion than indicated in the diagram. In this case the impedance locus will cross the (-X) axis at 6.0 per unit and swing into the – R region before returning to the initial load point.

Curve C is for the case where the machine is operating .95 leading power factor. As shown in this diagram, the stable swing cuts across the (– X) axis and swings well up into the third quadrant. Curves B and C will cut across both blinders and can cause the blinder logic to pickup. Tripping would occur if there were no CEB to limit the tripping zone. Curve C is of particular concern since it swings close to the origin and therefore will affect the setting of the CEB relay.

It should be noted that the "worst" case swing curve C occurred when operating the generator at leading power factor and when clearing a fault at the critical switching time which was 0.18 secs in this case. For faster clearing times and lagging power factors, the transient stable swings tend to follow the pattern of curve A. In any event, studies should be made to determine the "worst" case swing for a particular machine.

Relay Current Levels

As noted in the preceding section, relay current levels have some affect on the maximum slip the out-of-step relaying scheme can detect. In general, this will not be a problem for the normal application range of this scheme.

The current level of concern would be the current magnitude when the generator and system are 180 degrees out-of-phase. This current is approximately equal to

$$I = \frac{E'_q + E_s}{X'_d + X_T + X_s}$$

where I = per unit generator current

E'_q = per unit generator voltage behind transient reactance

E_s = per unit equivalent system voltage

X'_d = per unit generator transient reactance

X_T = per unit transformer reactance

X_s = per unit system impedance.

In this equation, the factor which will have the greatest influence on relay current is the system impedance. The maximum value of system impedance for which the scheme is required to operate would be where the system impedance equals the sum of generator and transformer reactances,

$$X_s = X'_d + X_T.$$

At this value of impedance, the electrical center is approximately at the high voltage terminals of the step-up transformer. Higher values of X_s would bring the electrical center out into the system where it is assumed to be outside of the required operating range of the out-of-step relay.

Considering a typical range of values for generator and transformer reactances, a range of generator and relay currents can be determined for the limiting condition, ($X_s = X'_d + X_T$). For example, for present day generators and transformers, the quantity ($X'_d + X_T$) will fall in the range of .35 to .55 per unit. If it is assumed that X_s will also have this range of values, and that the voltages (180 degrees out-of-phase) add up to 2 per unit, the generator currents will vary from 2.857 down to 1.82 per unit amperes. If it is further assumed that the CT ratio is such that full load current (1 per unit) produces 4 amperes secondary, the relay currents will vary from 11.4 down to 7.28 secondary amperes. For this range of currents, the CEX-CEB scheme should readily detect slips over the range of 4. to 7.5 slip cycles/sec. Of course, the actual relay currents can easily be determined from the required stability studies.

Determination of Relay Settings

The determination of relay settings for the CEX-CEB scheme is not a complicated procedure. Preliminary settings can be obtained by using a simplified graphical approach on an R-X diagram, and then the validity of these settings are checked with the results of the stability study.

While the CEX—CEB scheme is normally applied at the terminals of the generator, there are some applications where it can better be applied at the high voltage terminals of the step-up transformer. This will be brought out in subsequent discussions.

Graphical Procedure: In the simplified graphical procedure, the generator is represented by transient reactance (X'_d). This reactance along with transformer reactance (X_T) and system impedance (Z_s) are plotted to scale on an R-X diagram as shown in Fig. 10. The origin of the R-X diagram is at the terminals of the generator. If the system impedance is variable, the smallest system impedance should be used. This is to assure that the subsequent blinder settings will be able to detect the smaller impedance locus associated with small system impedances. This will become evident shortly.

Next, the total impedance line is drawn between points C and D. The angle of this line with respect to the horizontal axis gives the system angle. With the system characteristic established, settings for the blinders can be determined.

Blinder Settings: The distance N from the origin and the angle β of the blinder with respect to the horizontal axis can be adjusted separately for each blinder. the angle β is normally selected so that the blinders are approximately parallel to the total impedance line. The spacing between blinders is generally selected so that the blinders will detect an impedance swing when the angular separation (δ) between generator and system

is 120 degrees. This angular separation can be determined by drawing construction lines at points C and D that are 30 degrees from the total impedance line. The blinder settings are drawn at the system angle to go through the 120 degree points as shown in Fig. 10. It 'should be noted that the dashed line, which is a bisector of the 120 degree angles, goes through the impedance center of the system and would represent the path of the impedance locus for the case where the ratio of generator internal voltage to system voltage equals one (1).

CEB Setting: The CEB relay is set so that it will permit tripping for all impedance loci that will appear in the region from the high voltage terminals of the step-up transformer down into the generator. To accomplish this, the CEB is generally connected with its forward reach looking into the generator and with its offset adjusted to emcompass the transformer reactance with some margin.

The forward reach of the relay should be set so that it will detect all impedance loci that can go through generator but not operate for stable transient swings. A forward reach setting which is equal to two to three times generator transient reactance (X'_d) would meet this criteria. Figure 12 illustrates this point by showing the proximity of the "worst case" stable swing with a CEB having a forward reach setting equal to three times generator transient reactance. It is obvious there is ample margin between relay characteristic and swing.

The offset must be adjusted so that it will detect an impedance locus that will go through the high voltage terminals of the step-up transformer. A setting which is equal to 1.5 to 2 times transformer reactance will usually accomplish this purpose. With the proper setting, the offset circle should be outside the blinders for swings going through the high voltage terminals of the transformer as shown in Fig. 10. This spacing assures that there will be proper coordination between the CEB and the CEX for this extreme swing. It may be difficult to achieve this adjustment where the system impedance is large. This will be illustrated shortly.

It should be noted that in order to detect swings at the transformer high voltage terminals the offset setting reaches out into the system and therefore the scheme may detect a swing which is outside the generator zone. While this is a possibility, the probability of this happening is small since the impedance locus will be near the balance point of the relay where relay operation is slow. The chances are system relaying will operate before the out-of-step relaying scheme. If the scheme does operate for such swings this is generally accepted as a desired operation.

Verification of Settings: Once the settings have been completed, they should be checked with actual impedance loci produced by the stability studies. Figures 11, 12, 13, 14 compare the calculated settings with impedance loci for system impedances of .05, .09, .2 and .4 per unit on generator base. Except for the case where system impedance equals .09 per unit, these impedance loci are the same as those shown in Fig. 2 and described in the first section of the paper for the 475 MVA tandem compound generator. All impedances have been converted to secondary ohms.

Figure 11 shows the settings and swing for Z_{ss} = .05. As noted several times in the discussion, with the voltage regulator out of service and with low system impedance, the impedance locus tends to be small in diameter and therefore more difficult to detect. This point is readily apparent in Fig. 11. With the blinders set for 120 degree angle separation between generator and system (solid lines) the blinders are just barely able to detect the impedance locus. To provide additional operating margin, both blinders would be shifted to the right as indicated by the dashed lines. In addition, the forward reach of the CEB has been reduced to twice the generator transient reactance to assure that the impedance locus will leave the CEB characteristic and thereby permit tripping.

Figure 12 illustrates the application of the CEX-CEB scheme where the system impedance equals .09 per unit. In this case, the calculated settings would be satisfactory and would not require modification. Again, this figure shows there is ample margin between the stable swing and the CEB forward reach setting which is equal to three times transient reactance X'_d.

Figure 13 shows the application of the CEX-CEB scheme where Z sys = .2. In this instance, the calculated settings would also be satisfactory and would not require modification.

Figure 14 shows the application of the CEX-CEB scheme where the system impedance equals .4 per unit. In this instance, the calculated settings would be adequate but the spacing between the CEB and the blinder for swings near the high voltage terminals of the transformer might be considered marginal. The CEB is at its maximum off set reach of 4 ohms and therefore can not be increased further.

If additional margin is desired, the relays can be shifted to the high voltage terminals of the transformer as shown in Fig. 15. Now with a 3 ohm off set, there is more margin available between the CEX and CEB settings. This problem of spacing between the blinders and CEB at the extreme limits of possible swings will only arise for high system impedance.

It was noted earlier that when system impedance is variable, the smallest impedance should be used to determine the settings. In general, if the resulting settings are adequate with the small system impedance they will also be adequate with the higher system impedance. For example, if the system impedance can be .05 and .2 per unit, it should be readily apparent that the settings for the .05 system would be able to detect the larger impedance locus of the .2 system. On the other hand, if the relays had been set for the .2 system impedance (Fig. 13), these settings would not have detected the smaller impedance locus shown in Fig. 11. As a final point of interest, it should be noted that while

the simple graphical approach is an approximate procedure, it does give a fairly good indication as to where the actual impedance locus will go. As noted earlier, the bisector of the 120 degree angle between generator and system, will go through the impedance center of the system which would be the location of impedance locus for $E_G/E_{sys} = 1$. As can be seen in Figs. 11, 12, 13, 14, the actual impedance loci are only slightly below this impedance center. This is to be expected since as discussed in the first section of the paper, EG/Esys< 1 for the actual impedance loci.

SUMMARY

The primary purpose of the above discussion has been to provide general guidelines on the application of out-of-step relaying for generators. Such protection should be provided on the generator, if the electrical center during a loss of synchronism condition is located in the region from the high voltage terminals of the generators step-up transformer down into the generator. This protection may also be required if the electrical center is out in the system and the system relaying is slow or can not detect a loss of synchronism. Generator out-of-step relaying should be capable of initiating tripping during the first half slip cycle and when the angle between generator and system is 90 degrees or less.

It should be emphasized that the guidelines and data presented here are the results of generalized studies that do not consider the effects of all types and designes of generators and system parameters, or the interaction effect of other generators. These effects can only be completely determined by a study of a generator connected to a specific system. Therefore, it is recommended the user determine the actual loss of synchronism characteristic for each generator, considering the overall effects-of the system.

REFERENCES

1. “Loss of Excitation Protection for modern syncronous Generators,” by John Berdy, IEEE transactions, P.A.S. Sept./Oct. 1975
2. “The Art and Science of Protective Relaying” (book), by C.R. Mason, John Wiley and Sons, New York, N.Y.
3. “Impedances Seen by Relays During Power Swings With and Without Faults,” by Edith Clarke, AIEE Transactions, Vol. 64, 1945, pages 372-364.
4. “Circuit Analysis of A-C Power Systems, Volume II” (book), by Edith Clarke and John Wiley and Sons, New York, N.Y.
5. “A Model Power System - Part I - Design of Model Generators,” by G. L. Wilson, S.D. Umans. Conference Paper C75-174-7 - Presented at PES Winter General Meeting, January 1975
6. “A Model Power System - Part II - Design of System Elements and Test Results,” by S.D. Umans, J. Szagner, G.L. Wilson. Conference Paper C75-173-0 - Presented at PES Winter General Meeting, January 1975.

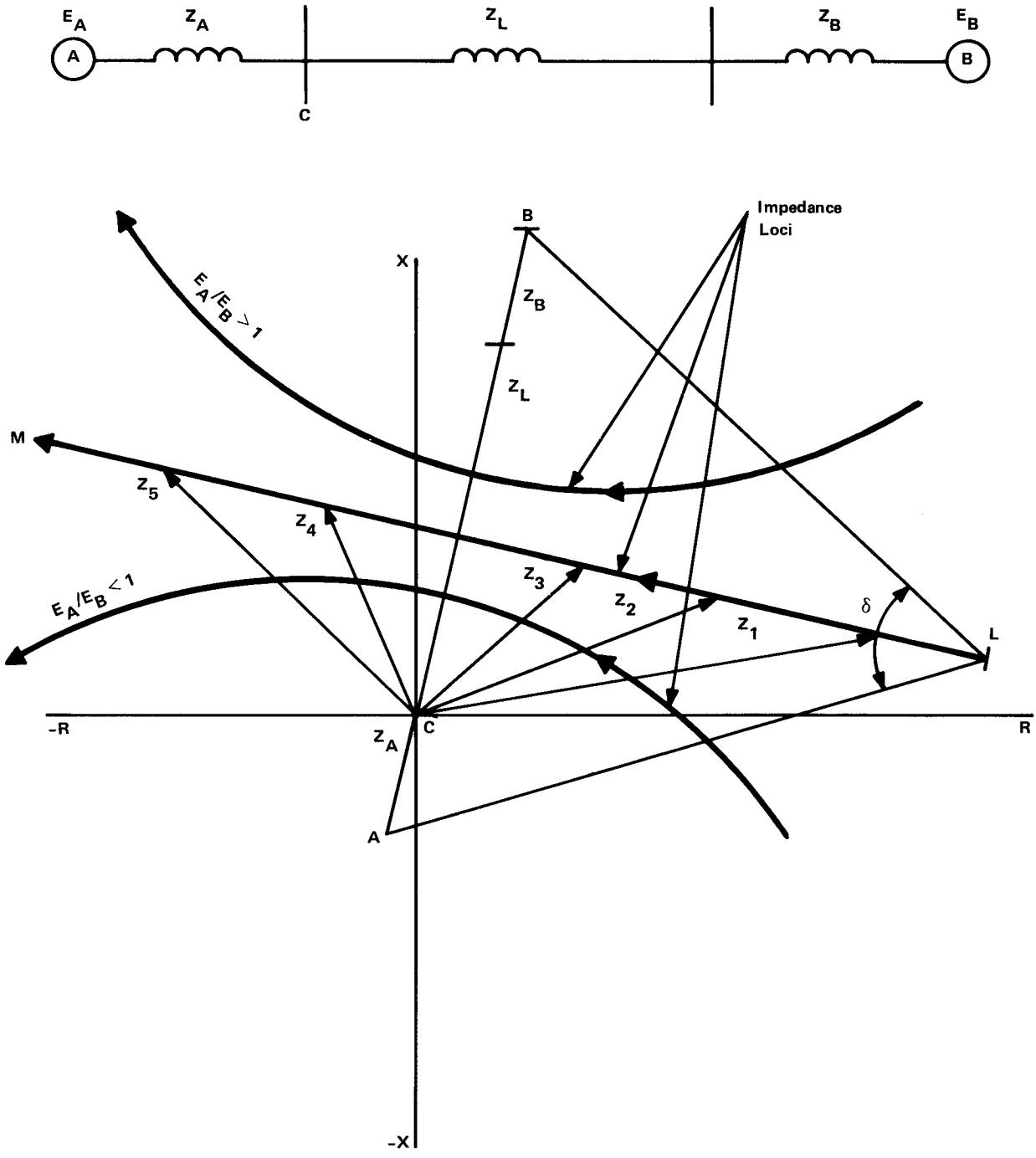


Fig. 1. Loss of synchronism characteristics as a function of voltage ratios

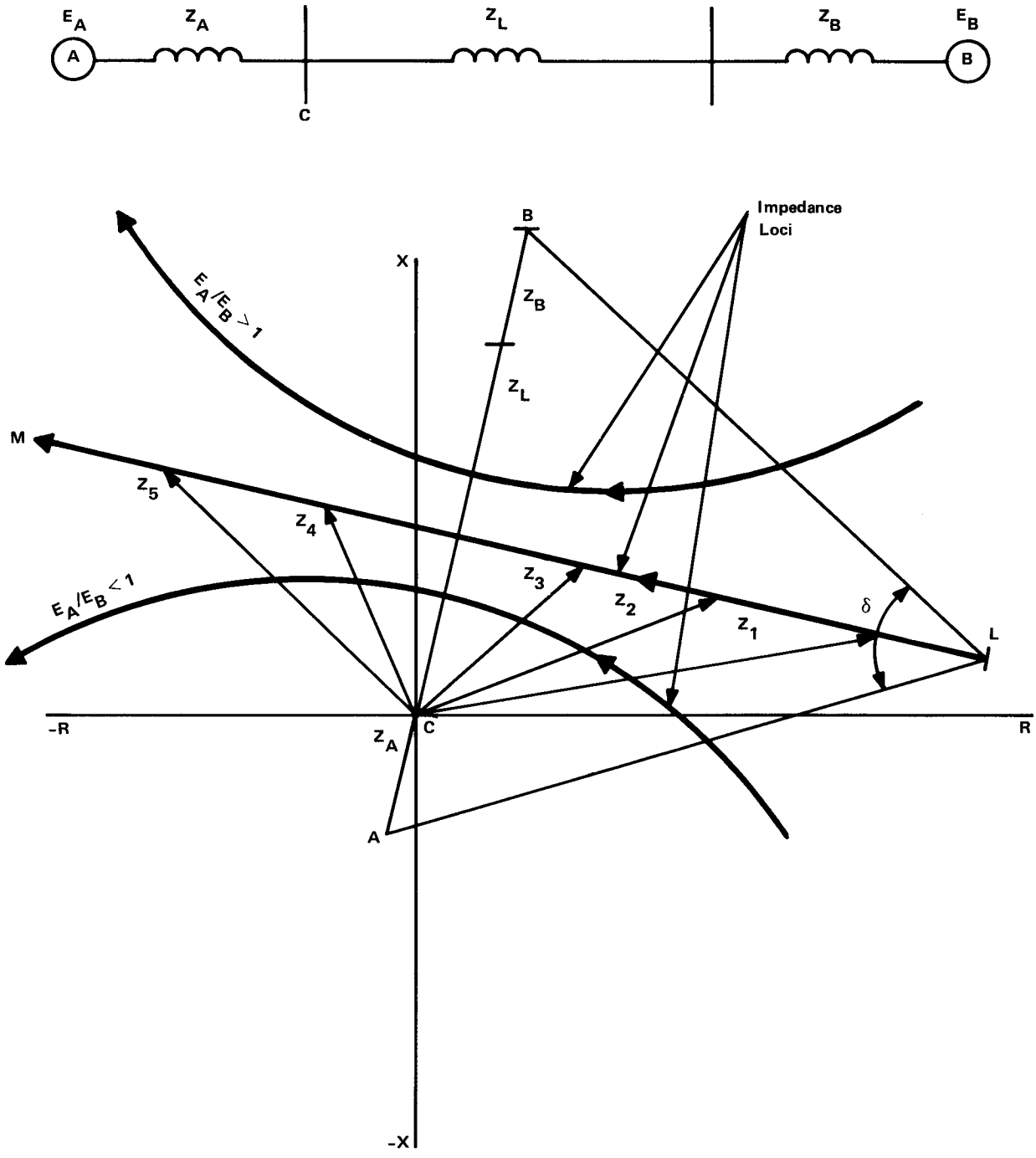


Fig. 1. Loss of synchronism characteristics as a function of voltage ratios

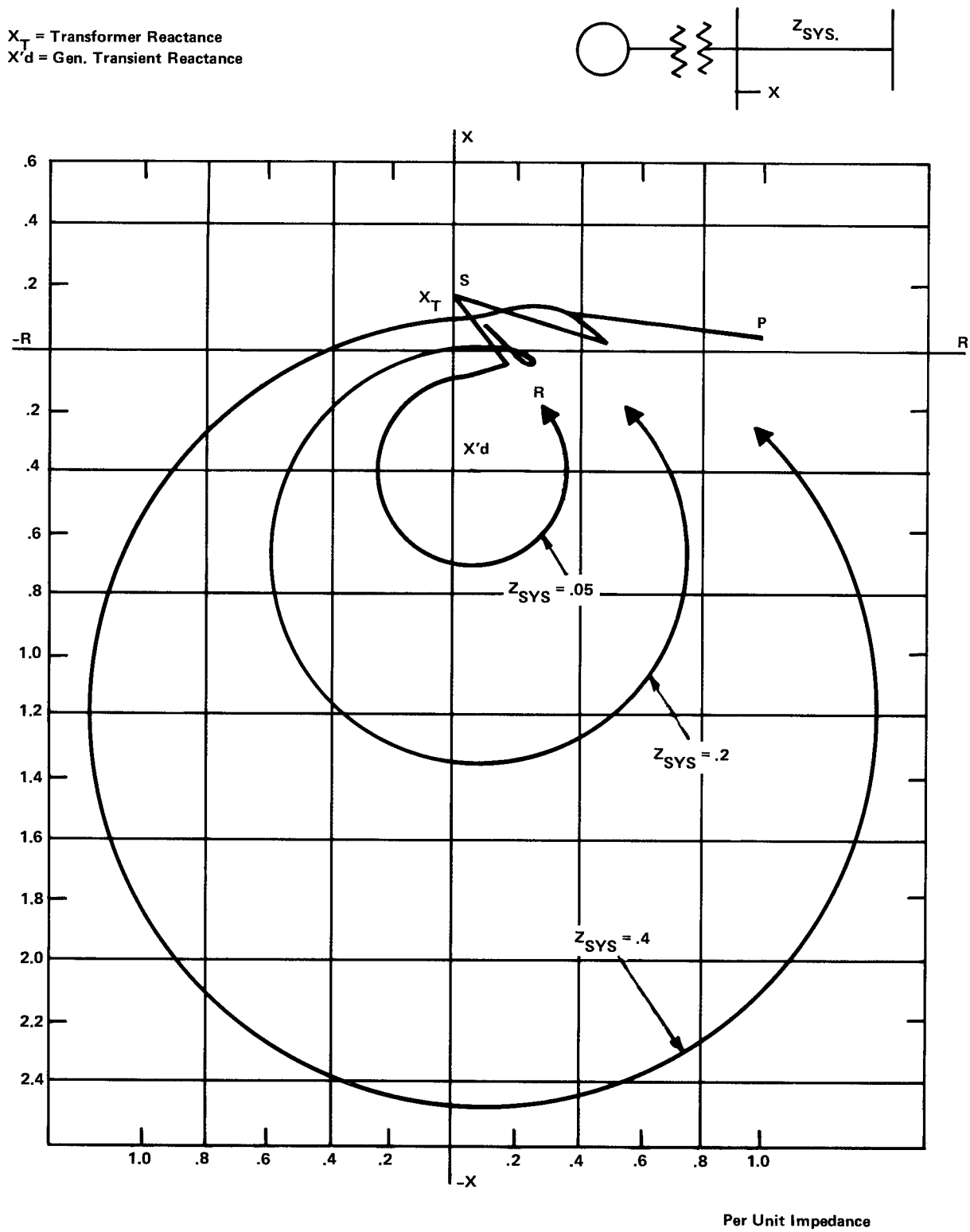


Fig. 2. Loss of synchronism for a tandem compound generator — voltage regulator out of service

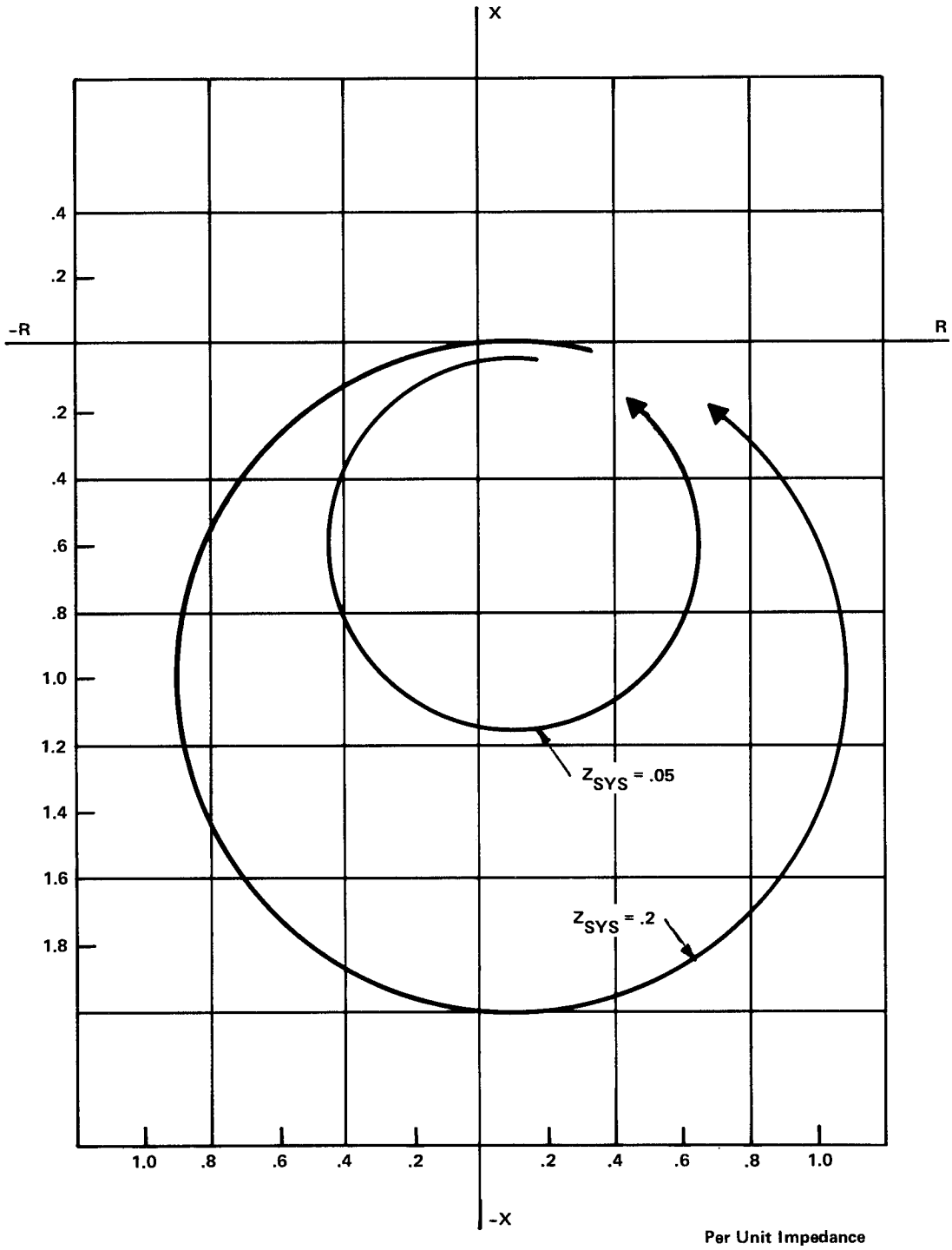


Fig. 3. Loss of synchronism characteristic for tandem compound generator — voltage regulator in service

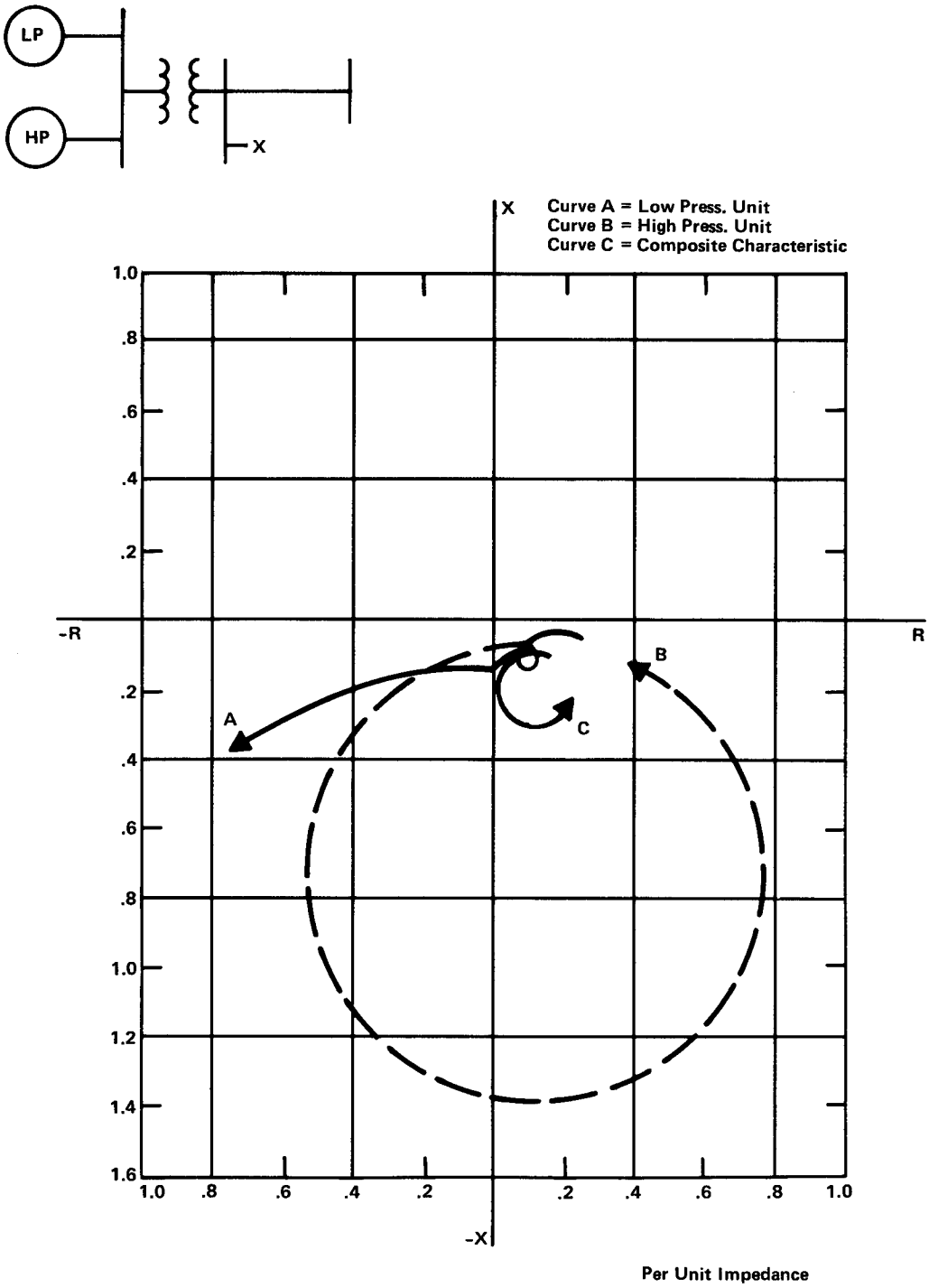


Fig. 4. Loss of synchronism characteristic — cross compound generator — $Z_{SYS} = .05$

Curve A = Low Press. Unit
Curve B = High Press. Unit
Curve C = Composite

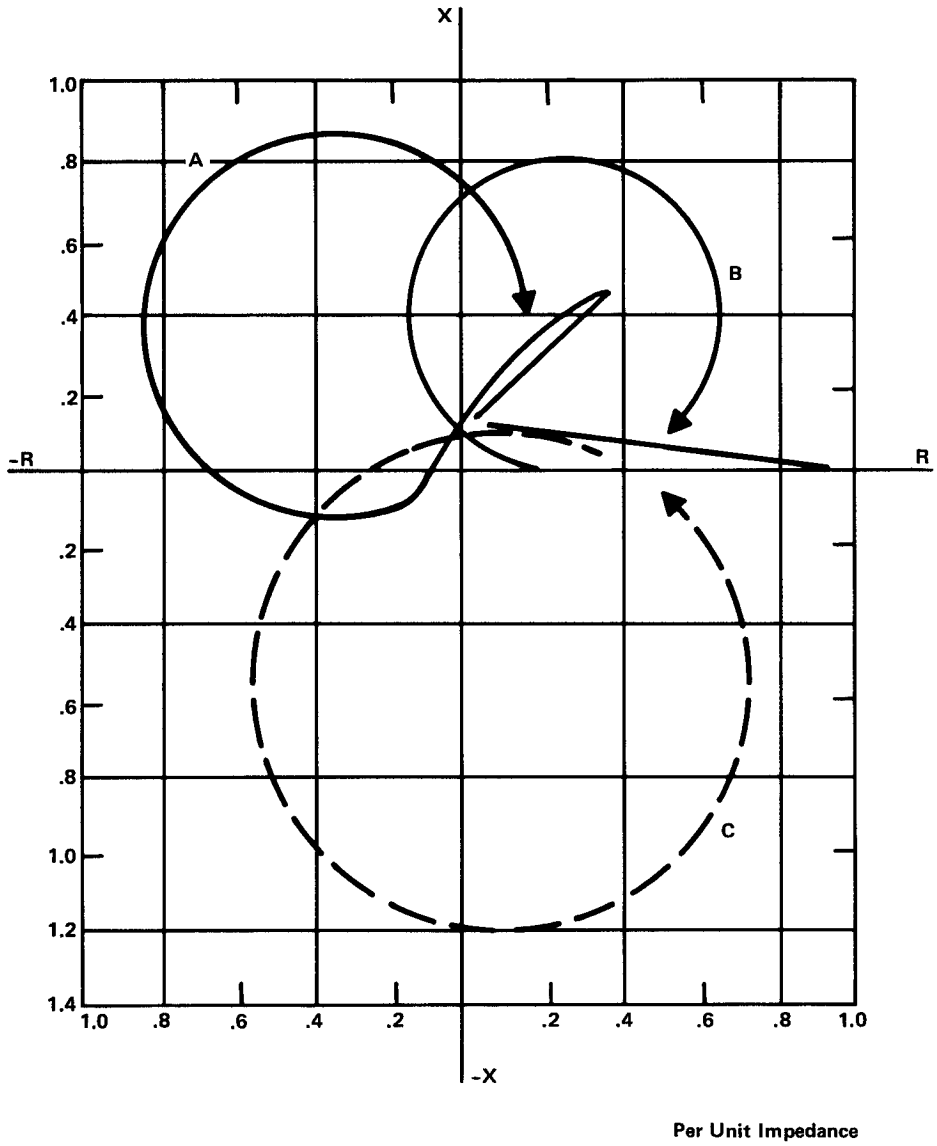


Fig. 5. Loss of synchronism characteristic – cross compound generator – Z_{SYS} = .2 to .4

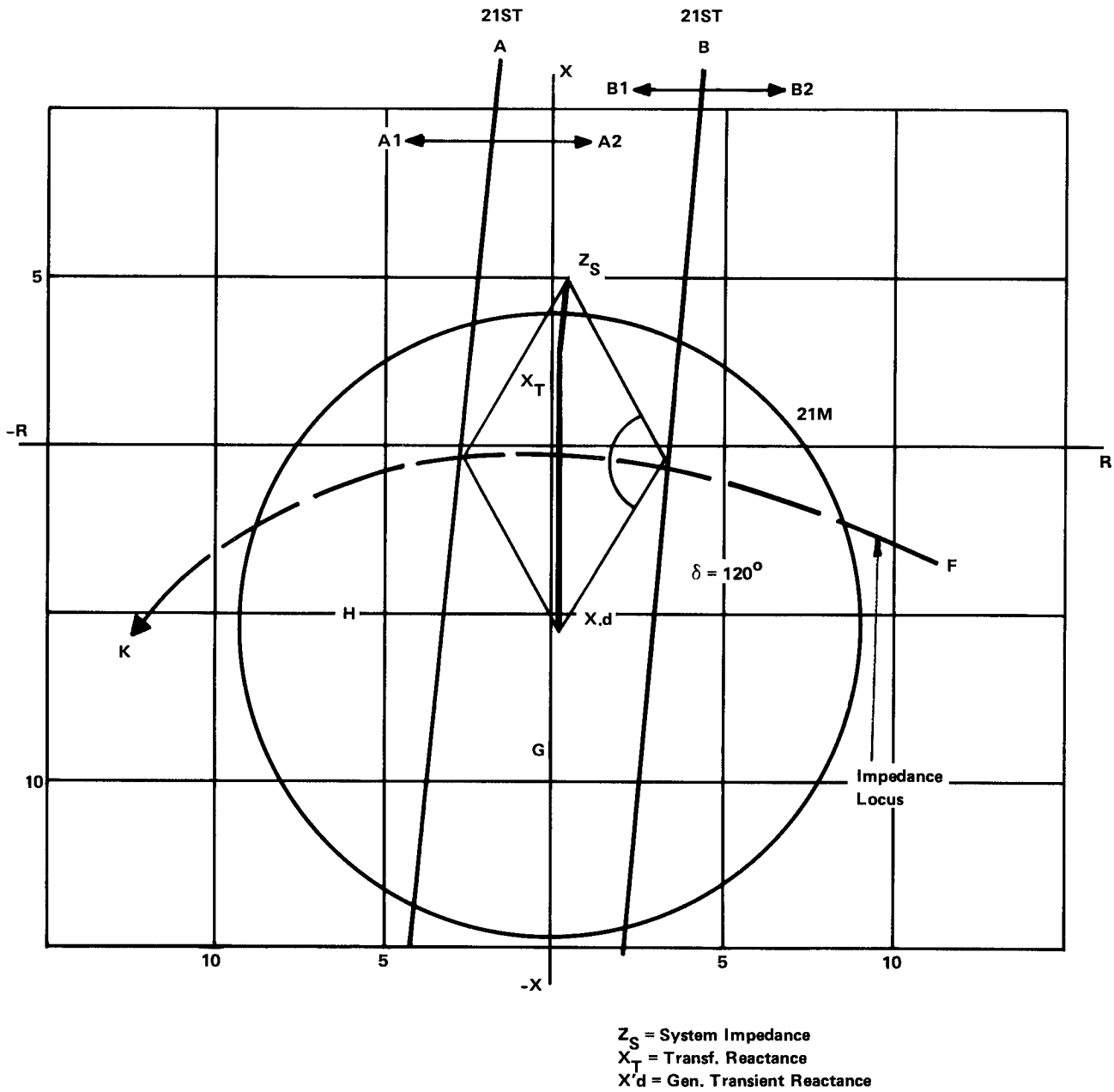


Fig. 6. CEX – CEB blinder out of step relaying scheme

21ST = CEX Blinder Elements
21M = CEB Supervising Relay
X_1, X_2, X_3, X_4, X_5 = Auxiliary Relays with Time Delay Dropout

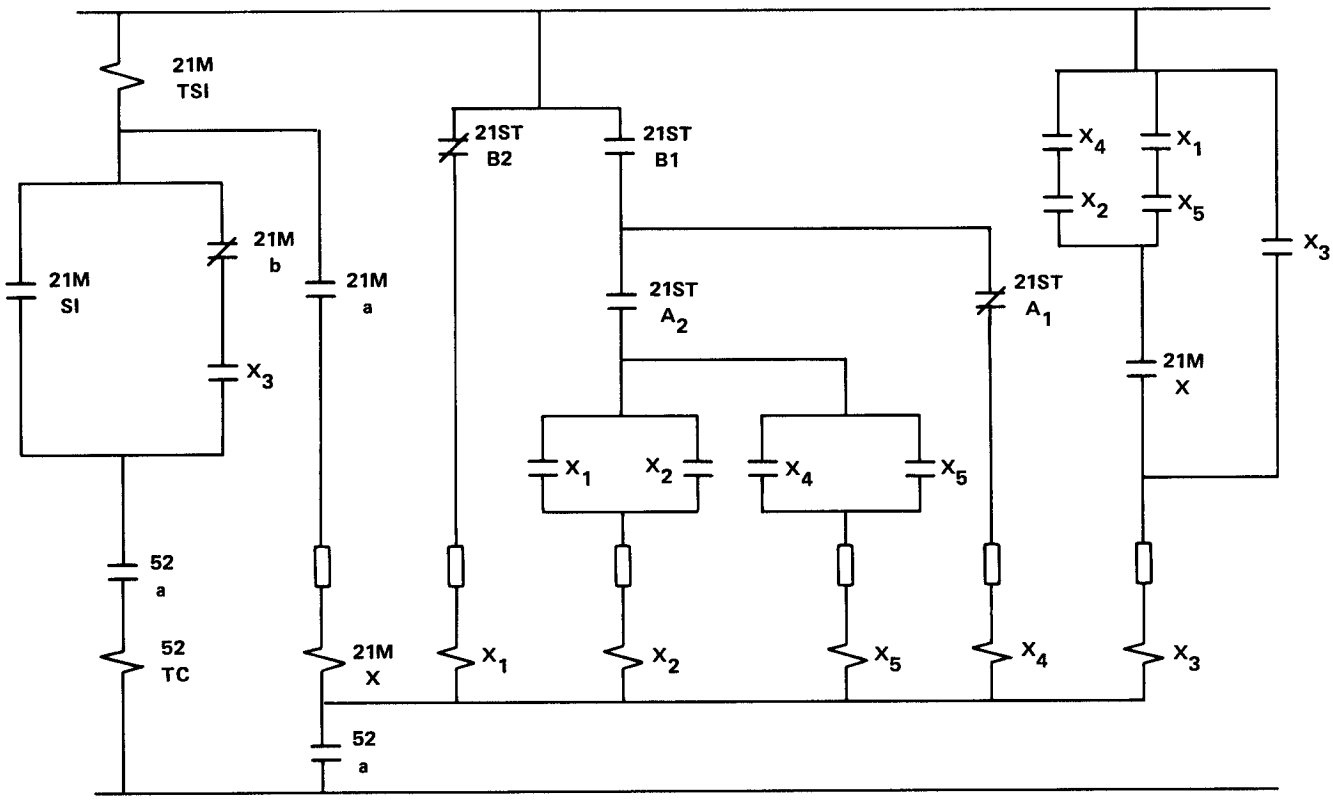
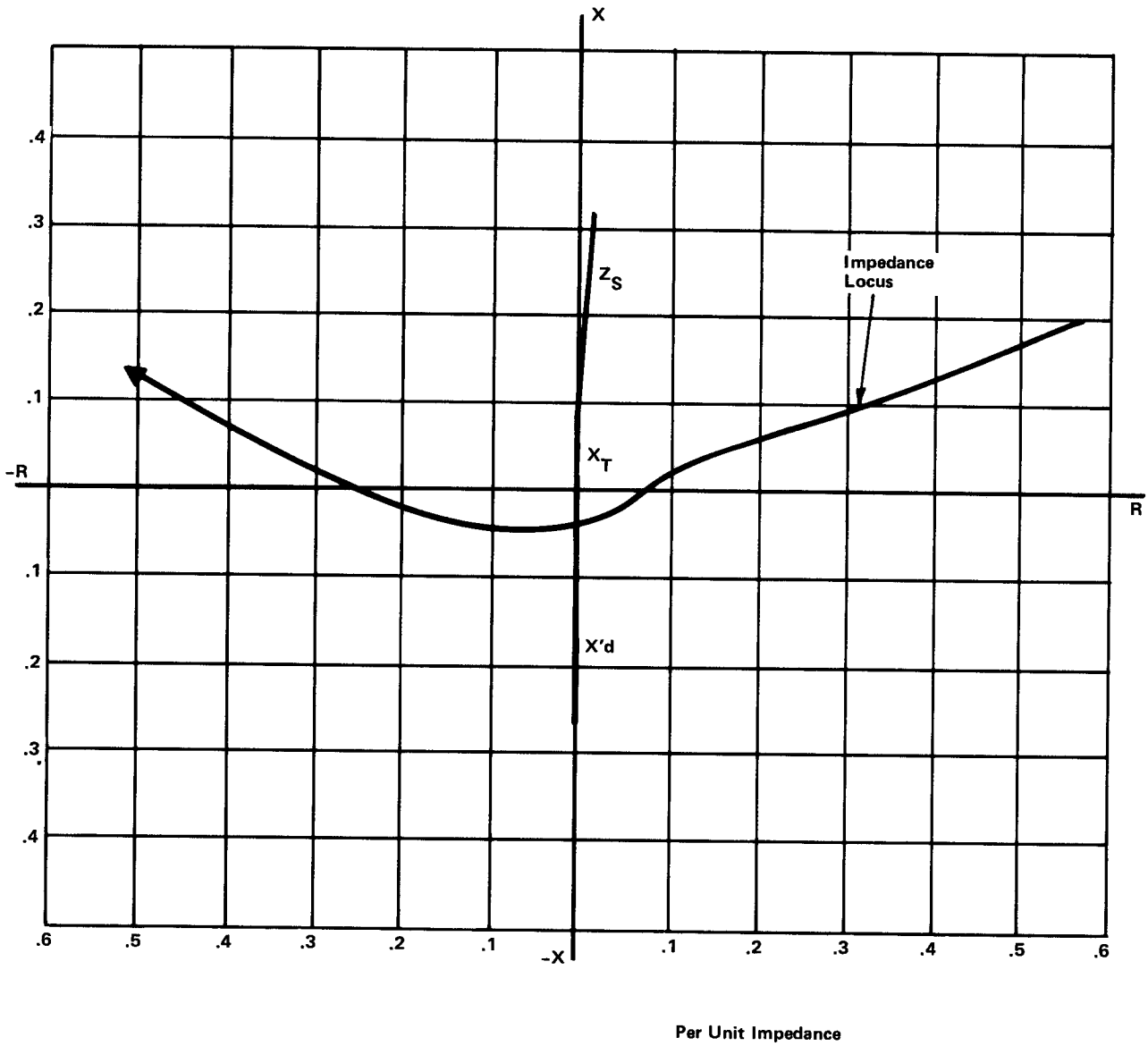


Fig. 7 – Logic for CEX-CEB scheme



Z_S = System Impedance
X_T = Transf. Reactance
X'd = Gen. Transient Reactance

Fig. 8. Impedance locus obtained from a system study

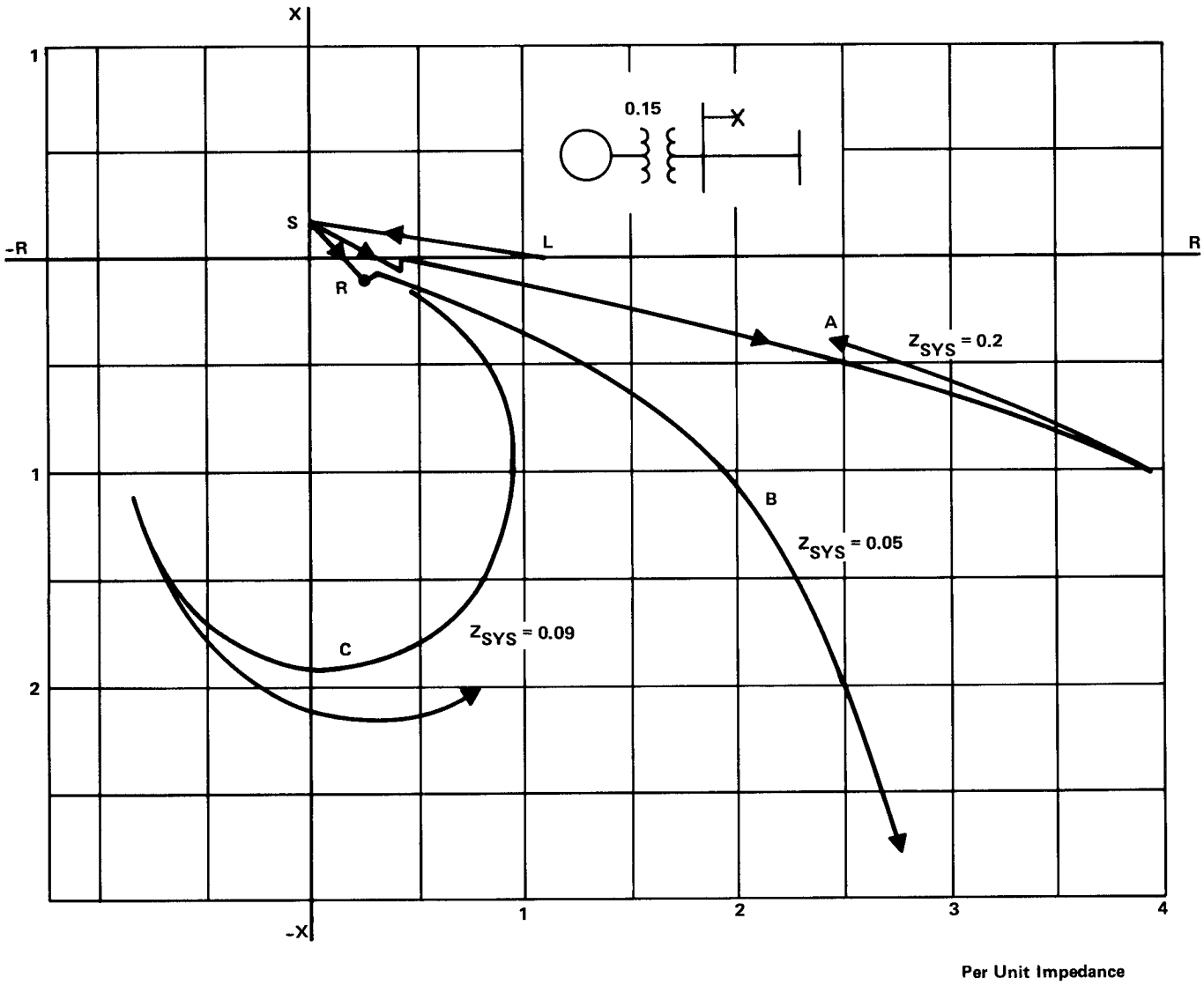
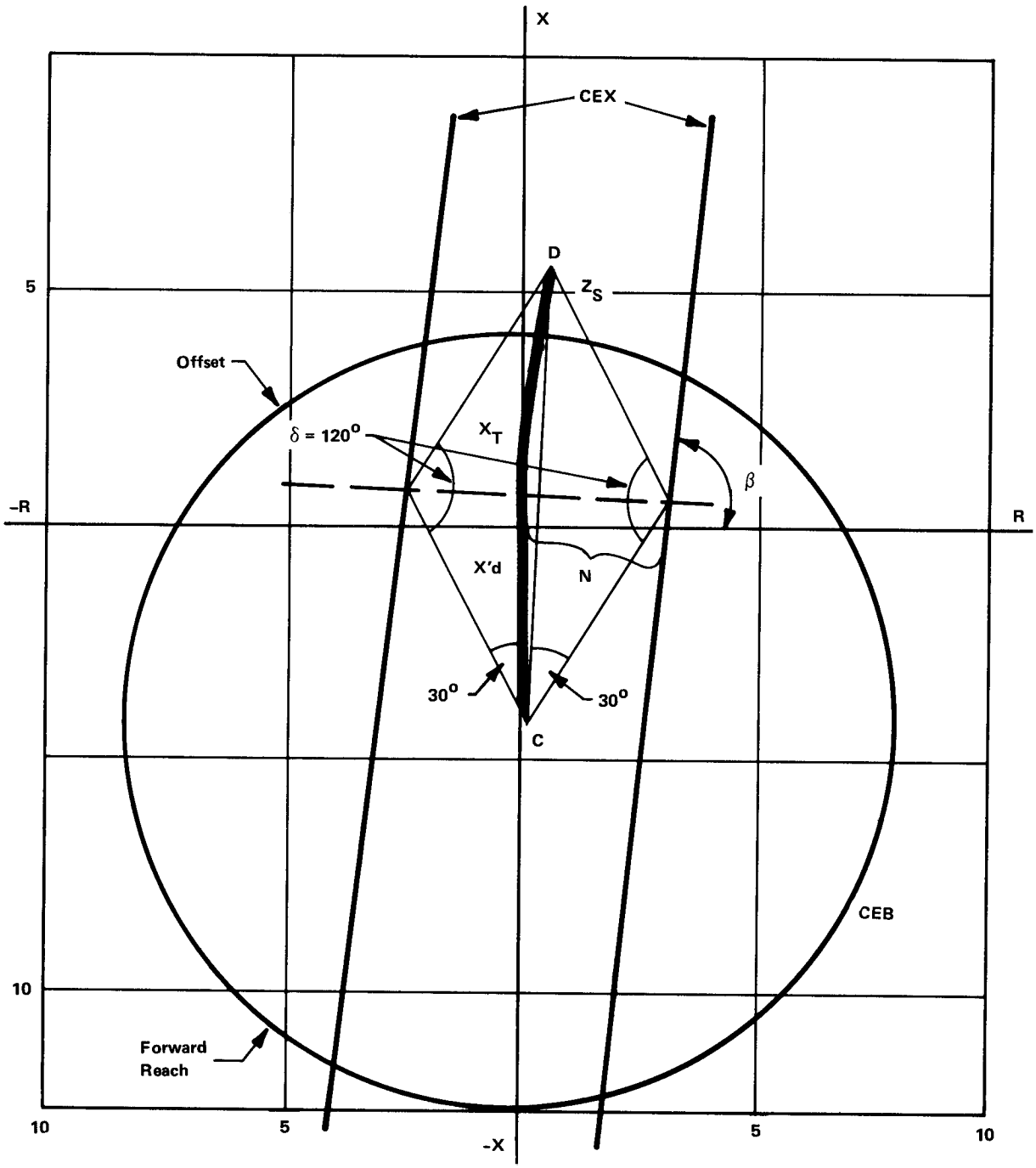


Fig. 9. Stable transient swings — tandem compound generator



Z_S = System Impedance
X_T = Transf. Reactance
X'd = Gen. Transient Reactance

Fig. 10. Typical settings for the CEX-CEB blinder scheme

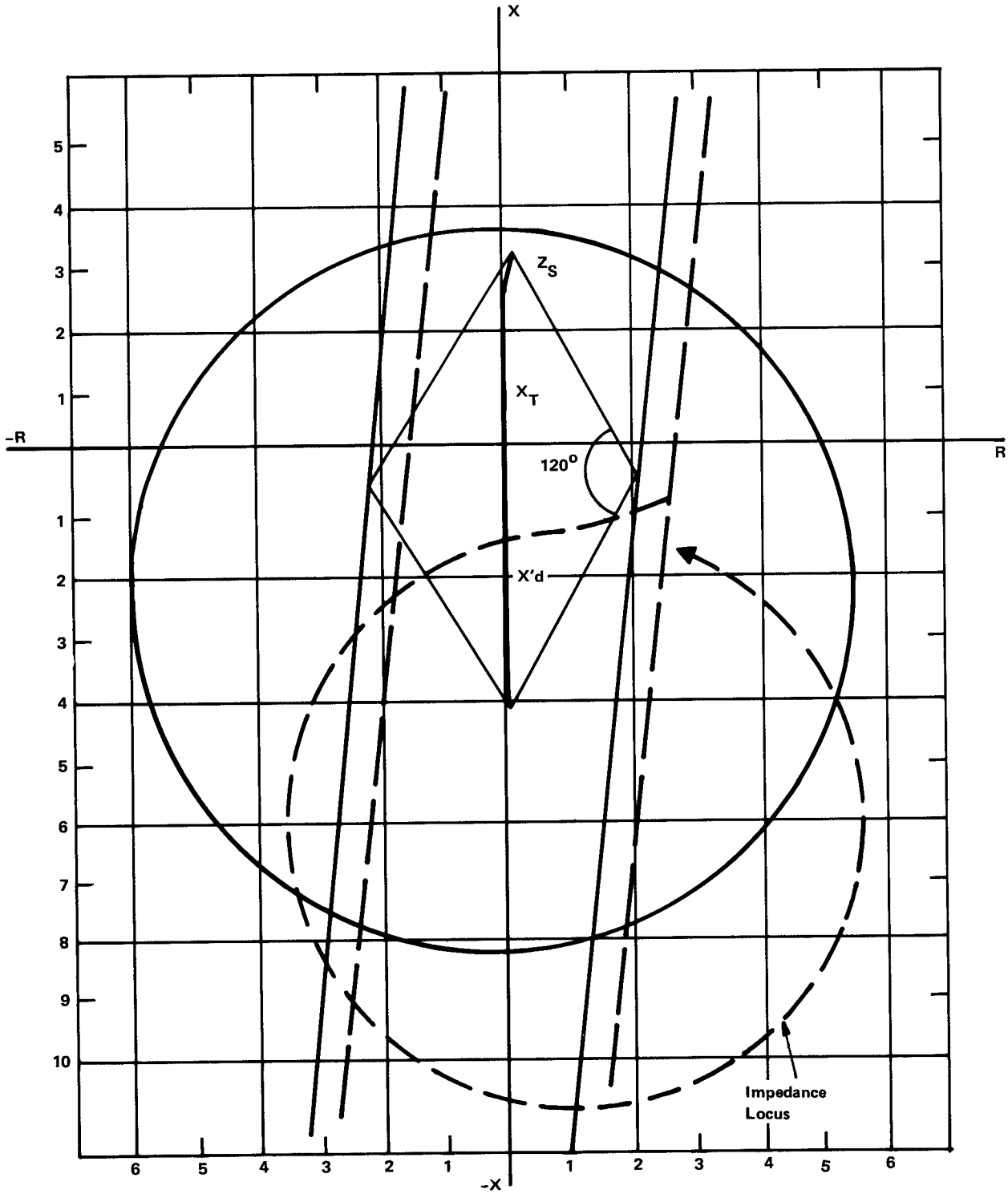
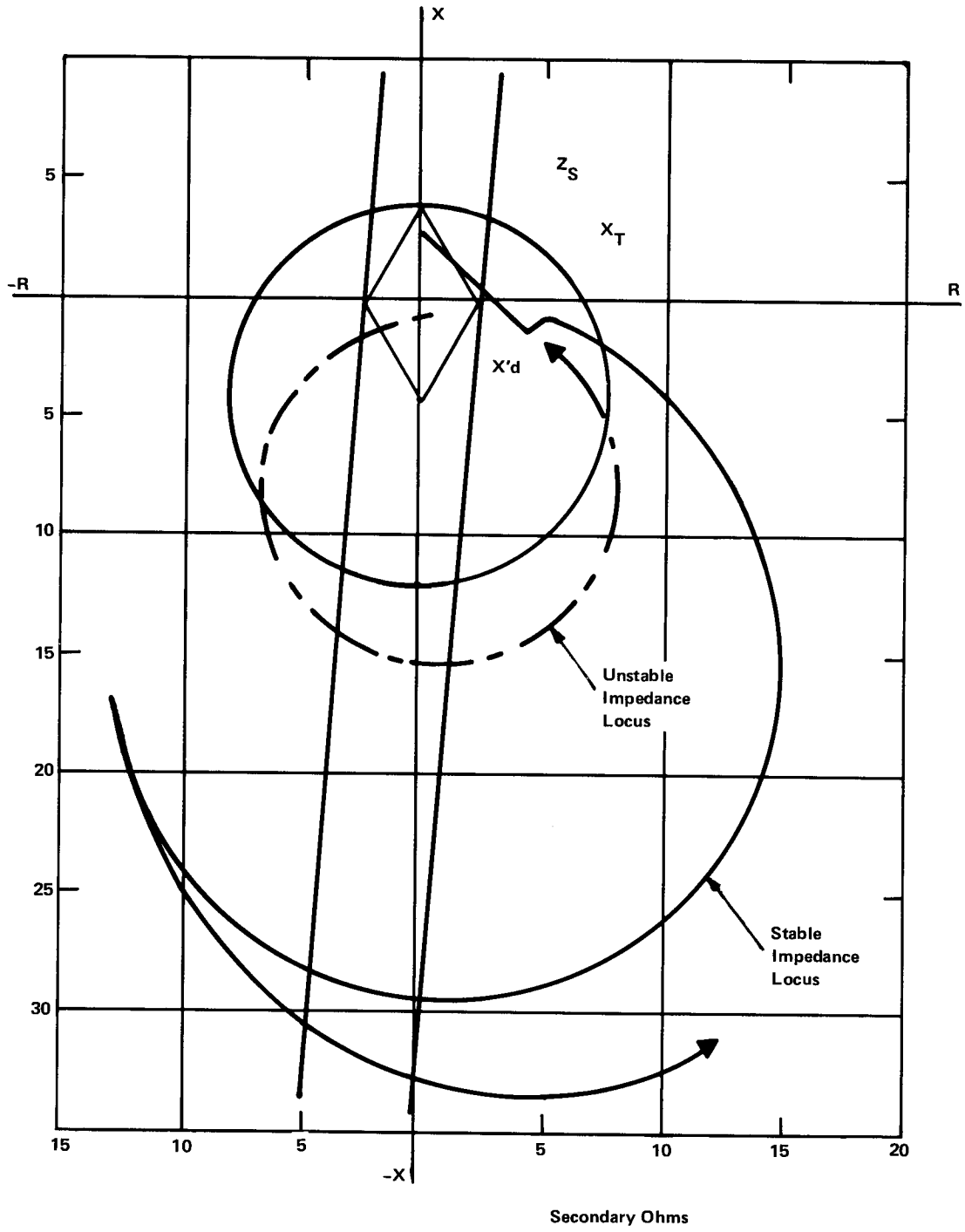


Fig. 11. Application of CEX-CEB scheme for system impedance of .05PU



Z_S = System Impedance
X_T = Transf. Reactance
X'd = Gen. Transient Reactance

Fig. 12. Application of CEX-CEB scheme – Z_{SYS} = .09 showing proximity of stable swing

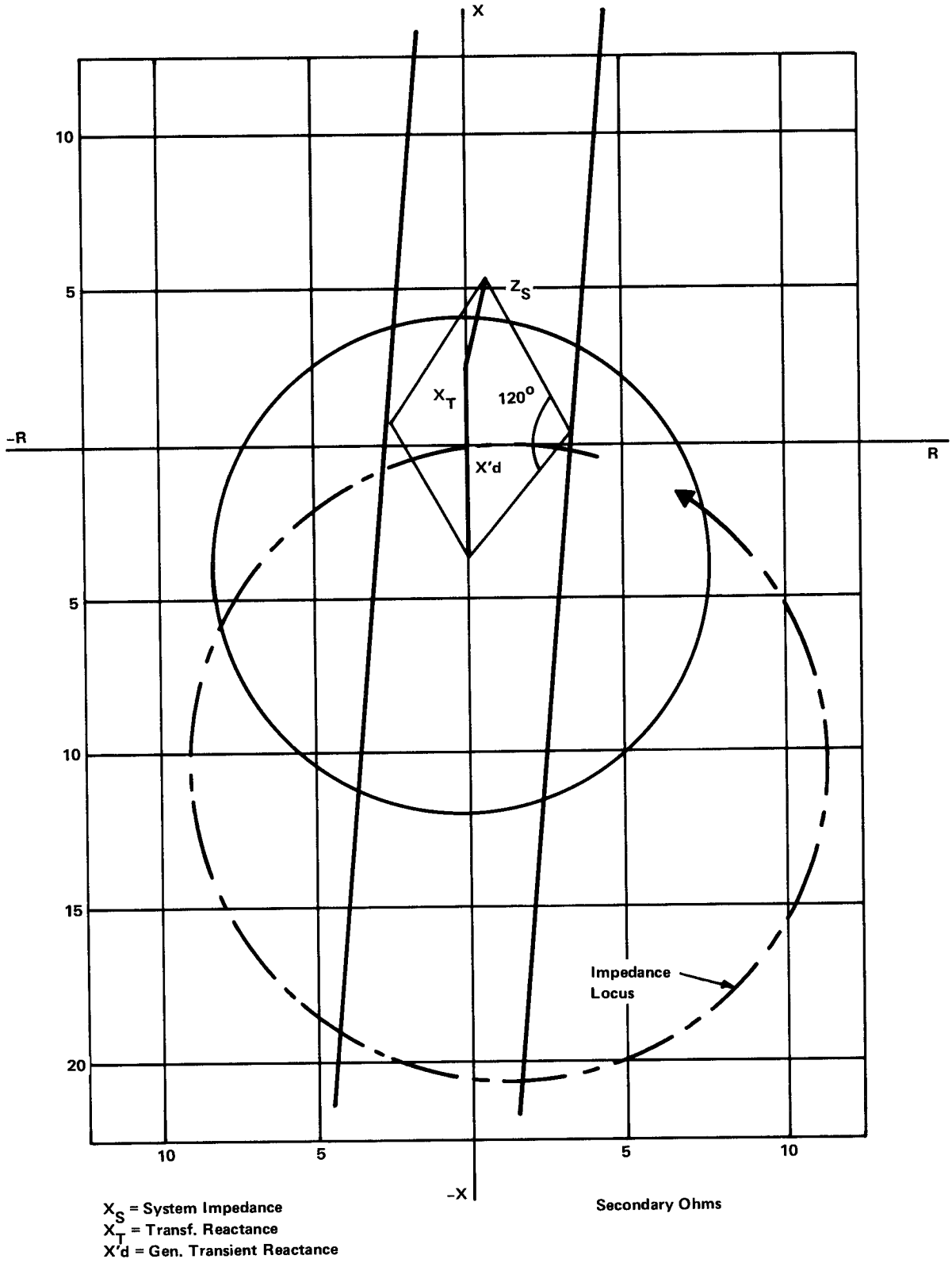


Fig. 13. Application of CEX-CEB scheme Z_{SYS} = .2

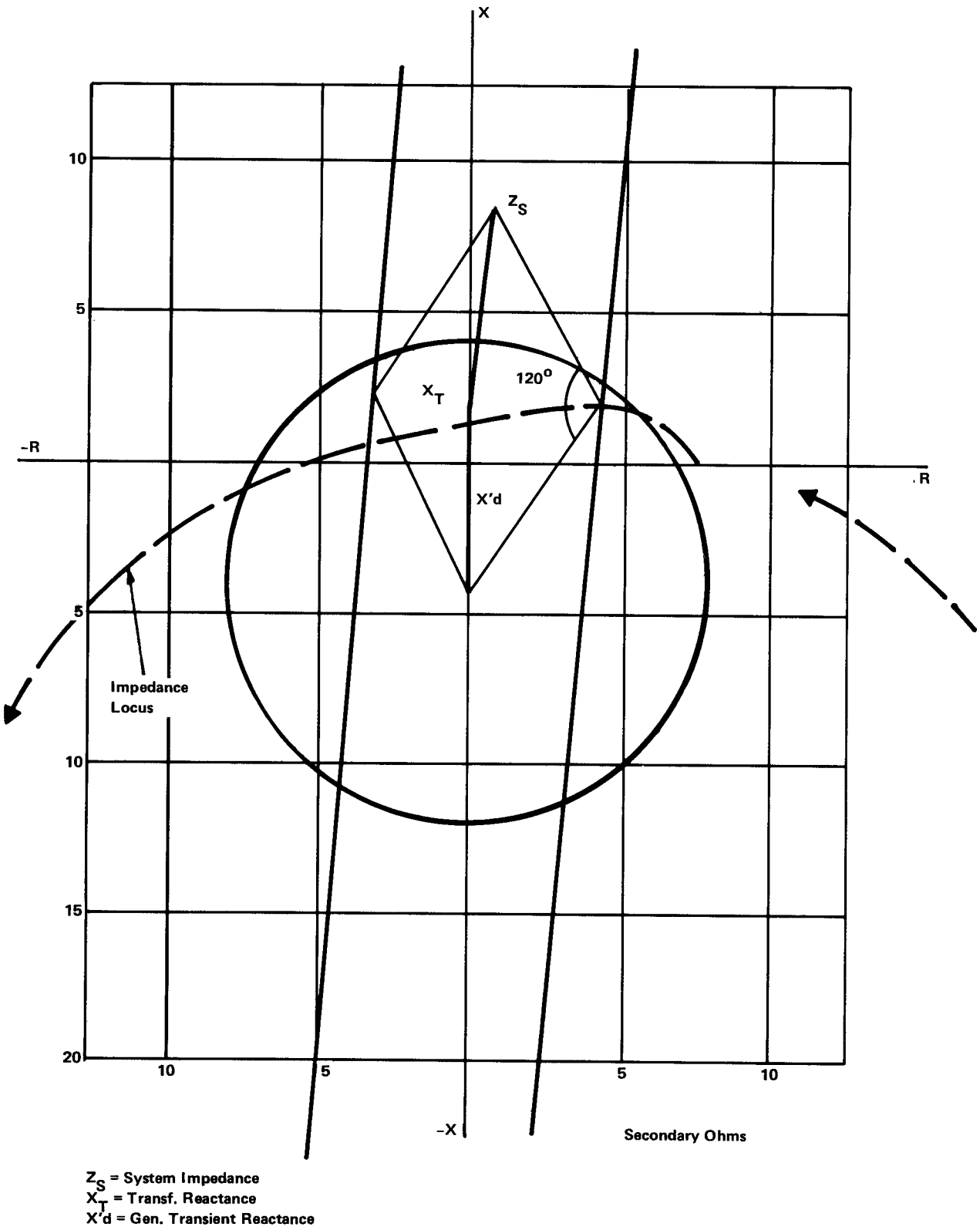
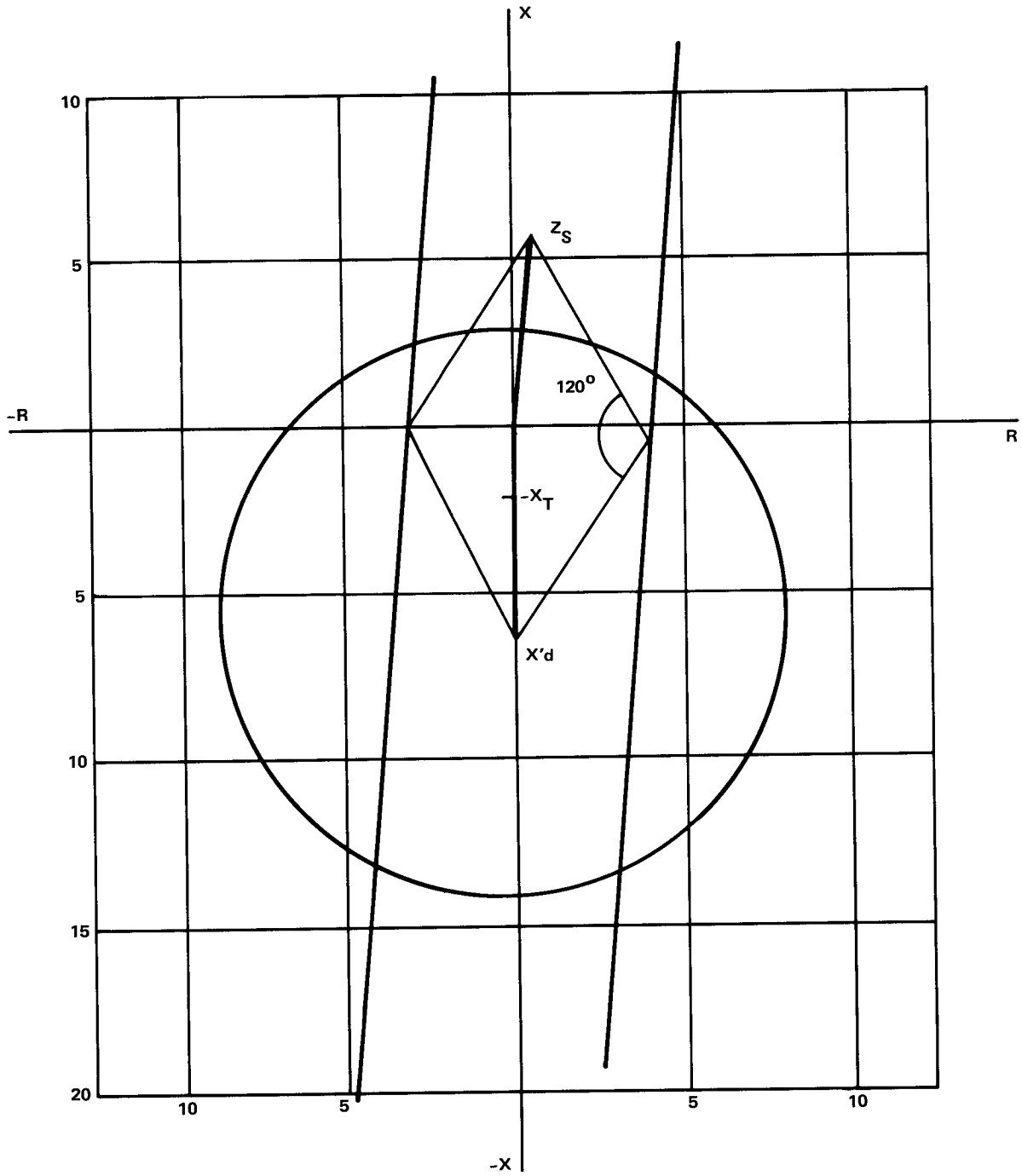


Fig. 14. Application of CEX-CEB scheme Z_{SYS} = .4



Z_S = System Impedance
X_T = Transf. Reactance
X'd = Gen. Transient Reactance

Fig. 15. Application of CEX-CEB scheme at high voltage terminals of step-up transformer Z_{SYS} = .4